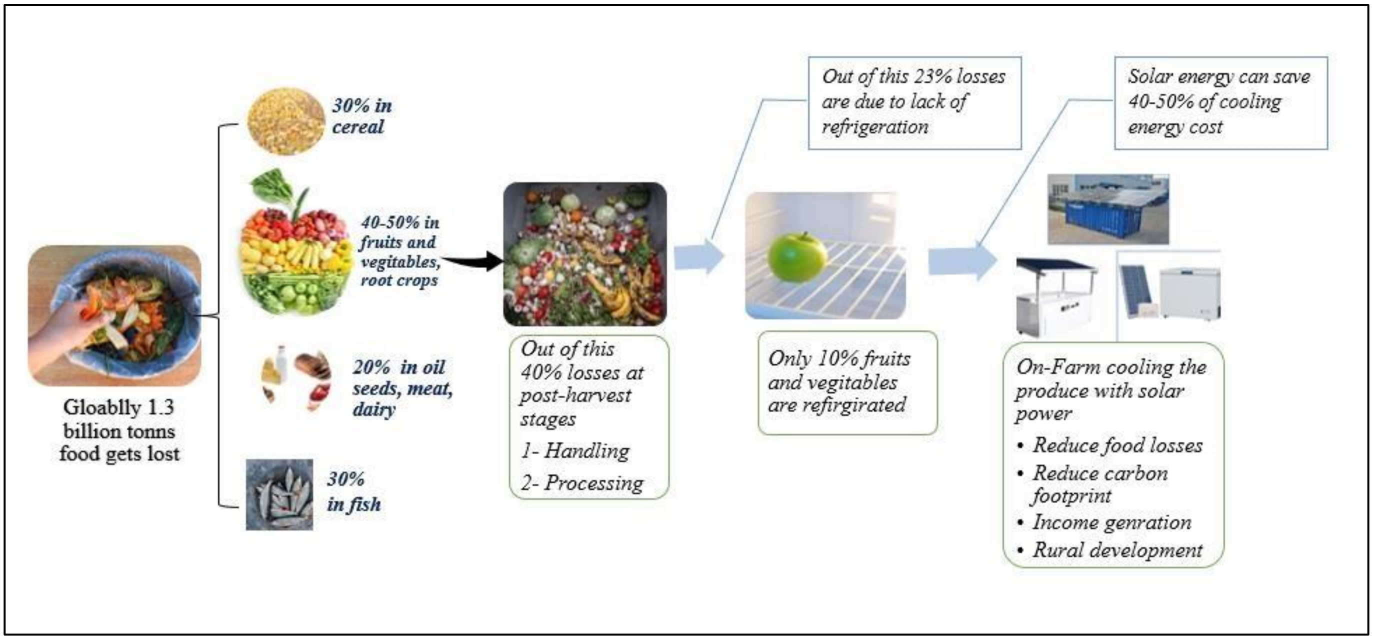
Abstract

Energy availability for on-farm storage and processing is a critical challenge smallholders face, which hinders agricultural productivity. Thirty per cent of food produced globally is lost postharvest, with the proportion being exceptionally high in low and middle-income countries (LMIC) due to a lack of on-farm handling and storage facilities. Conventional cold storage solutions have not taken off at the smallholder level in LMIC, particularly due to a lack of availability and access to reliable grid electricity. Therefore, off-grid decentralised solar-powered cold storage units can play a vital role in preserving the produce at production sites and enhancing livelihood and rural development with a minimal carbon footprint.

To maintain low temperatures throughout every step of the agricultural value chain, referred to as “cold chain”, several technology vendors aim to enhance product shelf life and user benefit. Smallscale farmers, who account for two-thirds of all food losses, are another group they focus on. This study examines the existing situation, importance, and potential opportunities of decentralised cold storage systems for fresh fruits and vegetables. In addition to economic, social, technological, and environmental limitations, this study examines the triumphs and challenges of incorporating solar energy-powered cold storage into developing communities. It has been found that although the private sector, NGOs, and some government agencies are working to promote decentralised cold storage facilities, relatively little has been done so far to have a significant influence on postharvest losses and food security. There are still knowledge gaps on decentralised cold storage facilities. The primary operational constraint is end users' economic situations and the lack of financing alternatives for smallholder farmers.



Graphical Abstract

Key words: post-harvest losses, Solar energy, on-farm cold storage**,** GHG emission

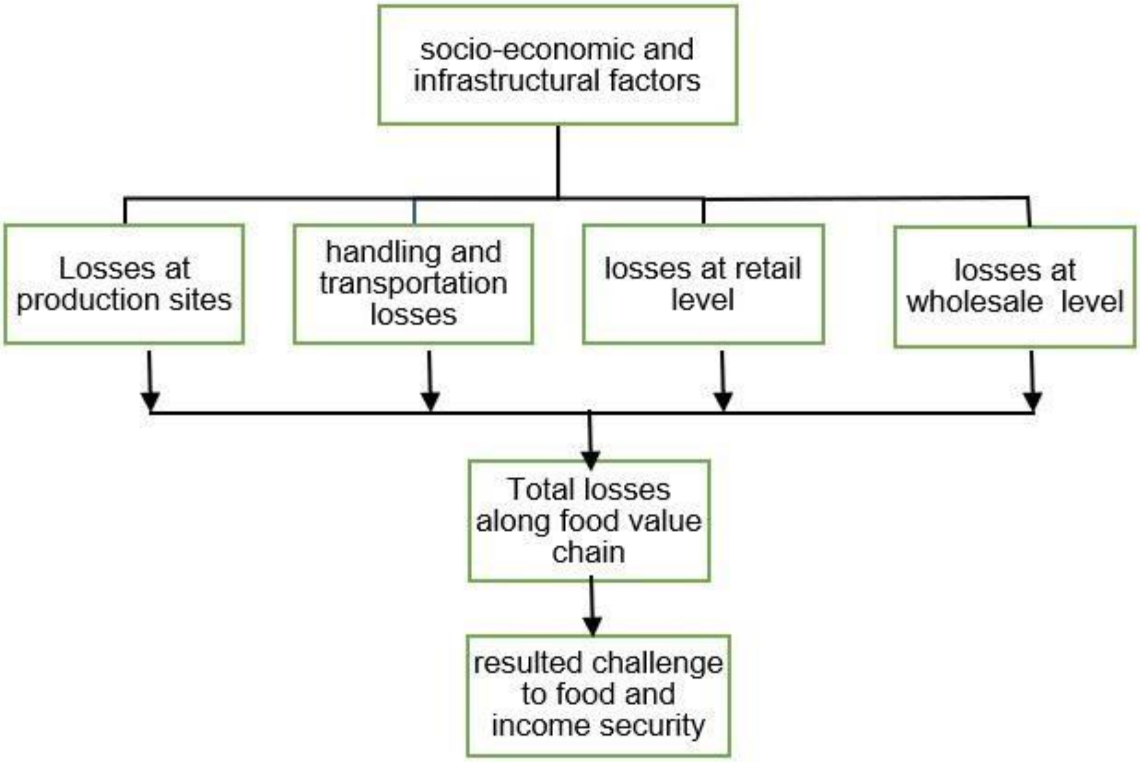
1. Introduction

With a steadily growing population, food and energy requirements are estimated to increase by 35% to 56% between 2010 and 2050 [1]. Even though the population growth rate from 2007 to 2050 is estimated to be lower (50%) than the rate from 1963 to 2007; high growth rates are still expected in developing regions of the world like East and Southeast Asia and sub-Saharan Africa, suffering already with food insecurity [2]. Global food production has gradually increased due to technological advancement [3]; however, post-harvest losses remain significantly high. These losses are due to product weight loss, nutritional loss, and quality deterioration [4]. Depending on the product, area and economy, post-harvest losses in the food supply chain vary greatly. In the case of developing countries, a sizable proportion is lost, particularly in the case of perishable products such as fruits and vegetables, due to the lack of agricultural handling and storage facilities. In contrast, in developed countries, food losses are high on the consumer side and low in the mid-supply chain due to the availability of better infrastructure to manage the products [5].

Given the perishable nature of fruit and vegetables, the need for timely storage is of foremost importance, as not all harvested produce is consumed immediately. The lack of cold storage facilities is one of the leading causes of massive post-harvest losses in highly perishable produce like tomatoes, negatively affecting farmers' livelihoods and the sector's economic contribution [6].

Decentralised sustainable energy solutions for on-farm cooling systems and storage can play a crucial role in addressing this challenge, especially in underdeveloped nations where losses are incredibly high at this stage of the supply chain. Current estimates suggest that post-harvest losses in fruits and vegetables are 30-50% in Africa [7], 20-44% in South Asia [8] and more than 40% in Latin America [9]. Various socio-economic and infrastructural factors directly affect post-harvest fruit and vegetable losses in developing countries at the production level, handling and transportation levels, and retail and wholesale levels [10] as shown in Figure. 1 and Figure 2 [11].

Drying and cooling are standard methods to store horticultural products safely [12]. However, the drying process altered the product's taste, colour, and texture, whereas fresh food can be kept in cold conditions without deterioration or shrinkage. Fruit and vegetable rotting begin shortly after harvest; thus, farmers must sell their produce at a low price to traders and collectors who cannot store it themselves. A standard cold storage system requires a significant amount of energy, limiting its applicability to smallholder farms in developing countries. Furthermore, commercial cold storage warehouses are centralised, increasing producers' transportation expenses.



[13].

Figure 1. Impact of socio-economic and infrastructural factors on post-harvest losses of fruits and vegetables. (Figure adapted from Khurshid et al [9])

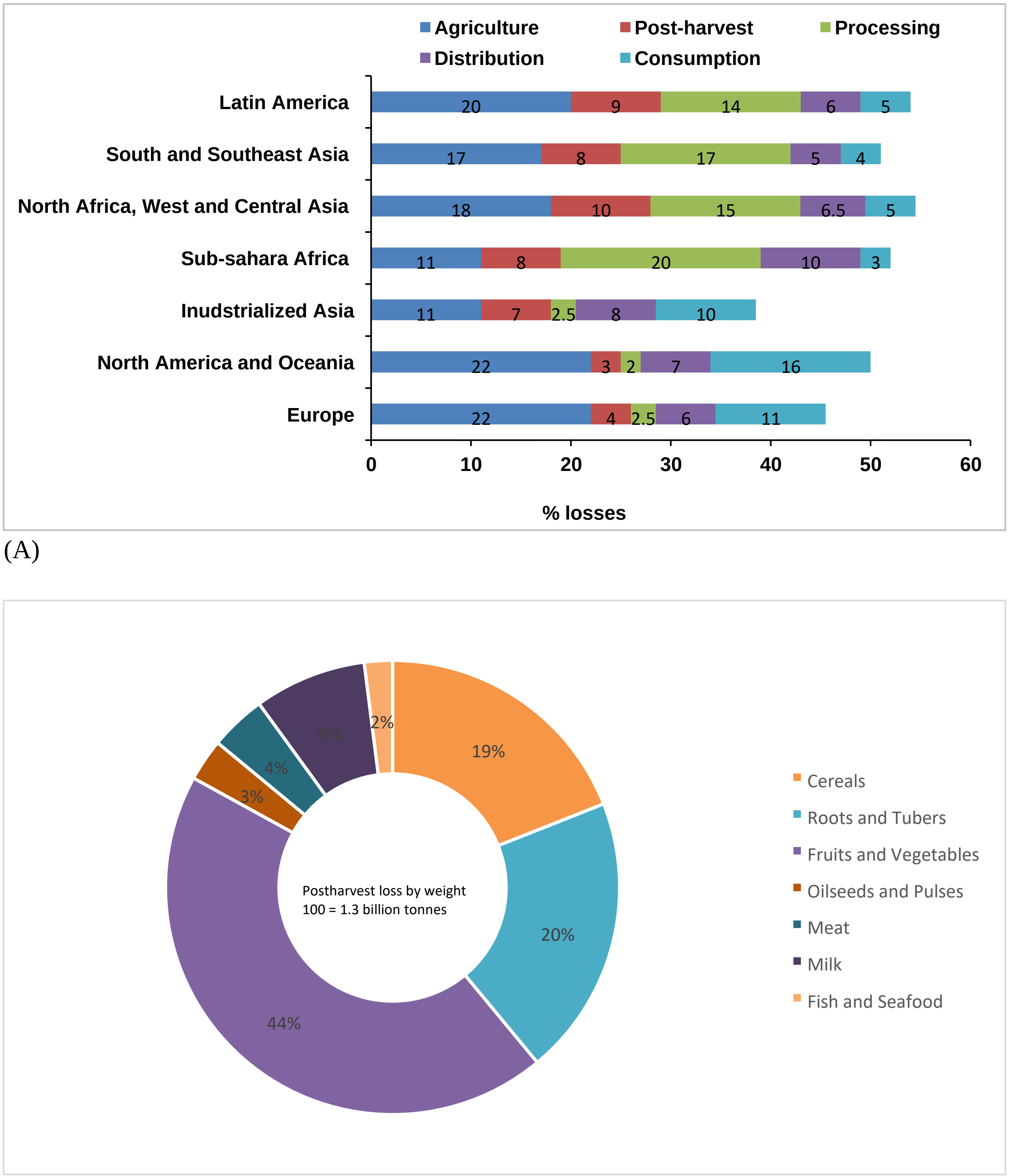
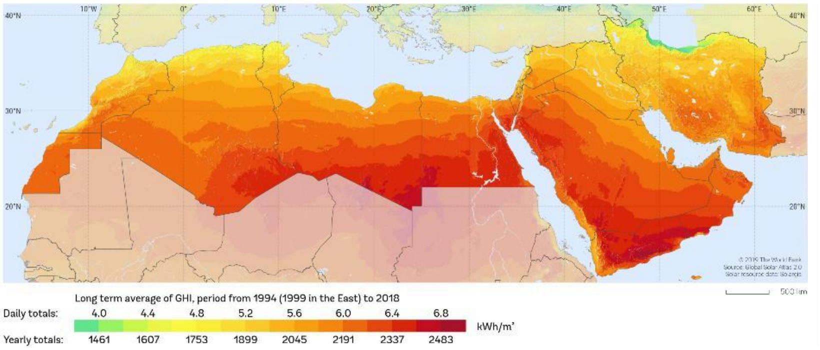


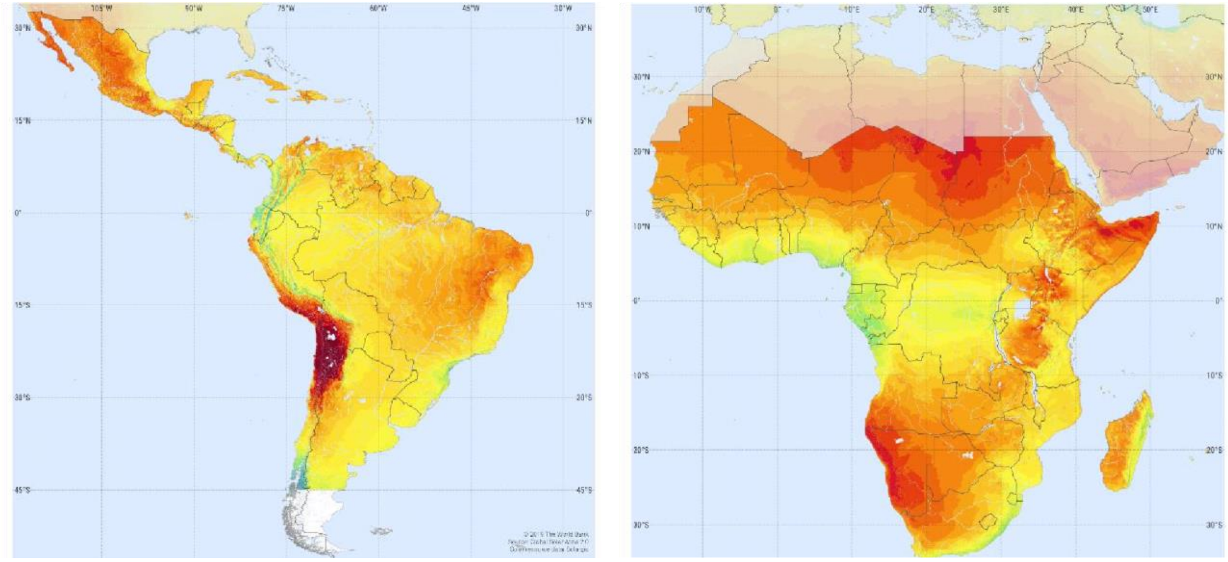
Figure 2. (A)Distribution of losses at various stages of the supply chain of fruits and vegetables in different regions of the world. (B) Share of global postharvest losses by commodities (Image adapted from Jose Graziano da Silva [10]).

Rural communities in underdeveloped nations are more susceptible to climate shocks due to a lack of cold storage facilities, which also causes more food loss. For instance, in Sub-Saharan Africa, food losses between harvest and processing are responsible for 37% of the region's food waste. The insufficient energy supply in rural areas, where most of the food is produced, causes disproportionately large losses. Therefore, decentralised cold storage can significantly help reduce post-harvest losses at their production sites and generate income and secure livelihoods in rural communities of developing countries [13]. Solar energy is a viable solution in developing countries, especially in tropical and sub-tropical regions in Asia, Africa, and Latin America. These areas receive a large amount of solar radiation all year round, an average of 4-7 kWh/m^{2}d, giving an energy amount of 19 MJ over the year [14]. Solar energy potentials in various tropical and subtropical regions of the world are shown in Figure 3. It depicts those developing countries have a higher potential of receiving enough solar energy to meet their demands than developed countries due to their geographical location.

It can be observed that the sunniest locations in the world are found in Africa. Theoretically, concentrated solar power (CSP) and PV energy in Africa are estimated to be 470 and 660 petawatt hours (PWh), respectively (IREA, 2014). The co-occurrence of solar radiation and cooling requirements makes it a desirable energy source that might reduce energy consumption for cooling processes by up to 40–50% [15]. Therefore, solar energy would be a great alternative to the traditional grid system for operating cold storage units in rural and remote areas.



(A)Middle East and North Africa



(B) Latin America and the Caribbean (C) Sub-Sharan Africa

Figure 3: Global horizontal irradiation (GHI) (source: Solargis, 2022 https://solargis.com/mapsand-gis-data/download)

The size of the global solar-powered cold storage market is anticipated to reach US$ 254, billion by 2027, expanding at a Compound Annual Growth Rate (CAGR) of 13% during the forecast period (Maximise market research Pvt. Ltd. 2021). The need of the hour is to invest in low-cost, decentralised cold-storage systems. Post-harvest technologies that are close to the farm gate or designed to meet the needs of smallholder farmers have the potential to increase farmer incomes and decrease food loss simultaneously. Efforts have been made to use solar energy for cooling in the forms of solar thermal energy [16], solar photovoltaic [17, 18], solar hybrid [13, 19], and solar hybrid energy storage with biomass heat [20]. To maintain the predetermined storage temperature in a solar cold storage unit, solar energy is captured and employed in a thermally driven chilling process. Applying solar cooling to perishable horticultural produce presents technical and operational issues, and it is crucial to control operational conditions to reduce the danger of product deterioration. One of the major constraints in utilization of solar cooling's in terms of economy and the environment is that standalone solar cooling systems are costly because of the battery backup size [21]. Furthermore, a lack of knowledge regarding solar-powered cold storage solutions impedes their future implementation [22]. Secondly, solar experts' concerns about high installation and deployment costs are exacerbated by additional market constraints, such as low purchasing power from potential customers and limited financing on renewable energy projects for local solar service providers. The social-cultural contexts and market conditions in different regions may prevent the eventual adoption of solar-powered cold storage solutions. However, it is predicted that solar electric cooling will require less cost in 2030 due to cost-saving advancements in photovoltaic technology and the high COP (coefficient of performance) of vapour compression refrigeration systems. Although solar cooling is considered promising for building cooling and centralised commercial uses, its decentralised applications in agriculture can play a vital role in addressing food security challenges in developing nations.

Considering the relevance of reducing post-harvest losses by using solar energy to store perishable fruits and vegetables on time, it turns into a need to know the pattern and scale of solar cooling techniques across the world, especially in developing countries, and identify its potential and a viable way forward for its promotion. Solar-based sustainable storage technological interventions may play a vital role in addressing product handling and storage at production sites. In the past, there have been several attempts to develop and disseminate solar cooling technologies for farming communities in developing countries. There is no collected information on the efficacy and state of these technologies, together with potential obstacles and chances of successful deployment. This study provides an overview of decentralised solar cooling technology interventions, adoption, and scalability for various horticulture products in developing countries, as well as implementation challenges in terms of technical, social, economic, and environmental factors. The rest of the paper is structured as follows: *Section 2* presents classifications of solar cooling; *Section 3* highlights the importance of this technology. *Section 4* discusses successful case studies in Asia, Africa, and Latin America, Section 5 presents potential operational constraints and opportunities, and *Section 6* concludes the study.

2. Low-technology solar-powered cooling options

The food chain has become increasingly dependent on refrigeration. It is employed in the food supply chain from processing to retail to end users in homes [23]. Solar energy can be used for cooling via solar thermal and PV modes [24]. A solar thermal driven system is more energy efficient than a system powered by PV due to higher solar thermal efficiency (more than 40%) than PV panels (efficiency 10-20%) [25]. The cooling process is highly energy-intensive and involves unit operation requiring a reliable supply of electricity. Small-scale farmers in developing regions typically lack access to reliable grid electricity, hence decentralised off-grid system can be of benefit. Table 1 summarises the low technology options and are feasible for small-scale farming operations [26].

Table 1. Cooling technology options for small scale farmers in developing regions.

Cooling technology	***Description***	***Temperature range***	***Energy options***
Passive or evaporative cooling	Operates in areas of dry and low humidity	10-25°C	no fuel (does not require electricity) architectural measures (shade creation, fountains, etc.)
Absorption refrigeration	Thermal-driven technology	below 10°C	solar kerosene
Refrigerators (vapour compression)	electricity-driven and therefore dependent on reliable electricity supply	0°C	grid diesel renewable sources (hydro, solar, batteries, etc.)

Four established cooling techniques are used to get cooling make use of solar energy: *vapor compression*, *sorption cooling* (including absorption and adsorption), *evaporative cooling* and *ejector cooling*.

2.1 Vapour compression

This refrigeration system consists of a compressor, condenser, an expansion valve, and an evaporator which are arranged in a closed loop to transform refrigerant (working medium) into various thermodynamics states for the exchange of heat from the space to be cooled [27]. Normally, ammonia gas is used as a refrigerant due to its low cost and high efficiency. During food storage, both the chilling (above 0°C) and freezing (below 0°C) processes are used to inhibit microbial and chemical activities. Although vapour compression refrigeration is commonly used and a mature technology,-it encompasses vibration and noise due to the operations of components.

2.2 Sorption cooling

Another type of refrigeration is sorption cooling which is thermally driven, and a thermal compressor (sorbent) is used instead of a vapor compressor [22]. Principally, this system can be *adsorption* (sorbent in solid form) or *absorption* (sorbent is in liquid form) in its working. As the system is thermally driven, this type of cooling is attractive using solar plants or solar heat collectors when the power supply is insufficient and costly.

2.3 Evaporating cooling

In these cooling systems, machines evaporate liquid (commonly water) to get the effect of refrigeration. During the evaporation process, the temperature of the substrate decreases due to the removal of thermal energy [28]. Such devices are used for air conditioning. Evaporative cooling can further be subdivided into direct, indirect and a combination of both depending on the nature of use. In the case of the direct evaporation method, the liquid evaporates directly from its source into the air and extracts heat energy from the space to cool down. But this process can increase humidity in space. When the liquid to be evaporated is not in direct touch with the environment to be cooled, indirect evaporation can be utilized as an alternative to prevent such circumstances. In a heat exchanger's stream channel, where water evaporates, the air flowing in the neighboring channel is cooled. Evaporative cooling does not require solar energy directly, however solar thermal energy can be used to heat the substrate surface (which contains water) to enhance the rate of evaporation. Through evaporative cooling, the air cools and circulates in the space so it is further categorised as forced air cooling achieved by compelling the cold air to flow all around the product [29]. A fan is used to create a pressure gradient, and the rate of cooling and uniformity of the room's temperature are used to gauge the fan's effectiveness. The arrangement of stored products in the storage chamber is particularly important to ensure the proper circulation of cool air. In addition, various other factors affect cooling rates such as product size and shape, bulk storage or packed, thermal properties, final desired temperature, flow rate, relative humidity, carton vent area and temperature [30].

2.4 Ejector Refrigeration

An ejector refrigeration system works on the principle of the Venturi effect for cooling. It is a thermally driven technology where a fluid is directed through a nozzle-type ejector [22] Compared with a vapor compression system, its efficiency is very low due to low COP but on the other side, it is simple in design and has no moving parts. Its main advantage is that it can be easily used using solar energy or exhaust/waste heat above 80^{o}C, so-called solar ejector cooling. Solar ejector cooling devices range from small and simple-to-use machines to complex devices for industrial applications [15, 16].

3. Importance of solar powered cold storage

The significance of using solar cold storage for fruits and vegetables and its impact on the rural community has been described in four sub sections i.e., *product quality*, *economic value*, *environmental impacts*, and *social aspects*.

3.1 Product quality

Fruits and vegetables start to deteriorate just after their harvest. So, handling at production sites is important to reduce post-harvest losses. Lack of storage and processing facilities at the farm level contributes significantly (10 to 40 per cent) to overall losses of produced perishables. For safe storage, *temperature* and *humidity* are the two main operating parameters to be controlled.

The temperature should be lowered to an appropriate level to increase the shelf life of the product as it directly affects the rates of biochemical activities [31]. Temperature and rate of respiration are directly proportional, so the higher the temperature the more the product will degrade. As a result, storage temperature is controlled in accordance with the thermal load. Secondly, maintaining the required relative humidity (RH%) during storage is complicated. High relative humidity is needed during storage to prevent softening, juiciness, and wilting and to maintain the product's salable weight, taste, flavour, appearance, and nutritional content [32]. Factors affecting higher rates of moisture loss (or weight loss) include storage of damaged products, immature harvested fruits and vegetables, and high surface-to-volume ratio products such as leafy vegetables. Hence, a storage condition with hot temperature, low humidity and high airflow would increase the moisture loss rate. The operating condition which does not cause chilling injury to fresh produce is the most suitable one and any variation from the recommended condition is detrimental. Depending upon the type of product to be stored, pretreatment, initial temperature etc. storage conditions vary for fruits and vegetables. Yahaya and Mardiyya, [33] summarised storage conditions for many fruits and vegetables. Combining a controlled atmosphere (CA) with refrigeration is another strategy for reducing food quality changes including softening, yellowing, and other issues because it slows down the respiratory processes [32]. Further, the storage environment can be changed by changing the rate of ventilation, using a gas absorber (i.e., potassium permanganate) or using activated charcoal.

3.2 Economic value

According to estimates, production systems receive 95% of the global financing for research and development in the agriculture sector, while post-harvest systems receive the remaining 5%. This disproportionality resulted in tremendous post-harvest “technology gaps” and “skill gaps,” especially in developing countries [4, 28]. It is estimated that less than ten per cent of all perishable foods is currently being refrigerated, even though post-harvest losses add up to 30 per cent of food production worldwide [1,3,4] In addition to giving farmers the chance to boost their income, cold storage also contributes to a decrease in overall post-harvest losses. The importance of pre-cooling and cold storage is critical in tropical and subtropical regions that may require considerable energy due to hot and humid climates. So economically, there are two aspects to generate income; one is the decentralised storage of products to reduce losses and the second is the energy-efficient storage technologies to reduce operational costs.

In developing countries, the distribution and supply of electricity in rural areas are not dependable so the provision of cold storage facilities is often dreadful. This simply leads to the wastage of a huge quantity of fruits and vegetables and even affects the local market of these products with price fluctuation [34]. Introducing sustainable cold storage technologies for off-grid and weakgrid markets can facilitate farmers, processors, distributors, and retailers to take advantage of price fluctuations in the market. Sapna Gopal, [35] described a company, Ecofrost, in India, providing decentralised solar-powered cold storage facilities to farmers. Currently, the units are in operation on 35,000 farms, potentially saving 35,000 tonnes of perishables from going to waste. At the same time, these modules have generated 100 million kWh of clean energy. The cold chain requires investment, particularly in pre-cooling and transport refrigeration equipment. This might cut India's perishable food loss by 76% and CO_2 emissions by 16% [36]. Similarly, a report by The Renewable Energy and Energy Efficiency Partnership [39] which develop financing mechanisms to strengthen markets in low- and middle-income countries, estimated that the market potential of solar power cold storage units in Uganda can reduce post-harvest losses by 30% and increase product shelf life by 50%. It is estimated that a farmer can get a benefit of € 5250 annually for renting 1 m^3 of cold space. With more of the harvest available to sell, small-scale farmers can increase their income by 25% annually. Cold chain is the key to tackling the loss of perishable produce. In this regard, it is predicted that if developing nations implemented refrigeration technology on par with that in developed economies, around a quarter of all food waste in these nations might be eliminated [37].

3.3 Environmental impacts

FLW (Food loss and Waste) are a significant driver of climate change. The current estimate suggests FLW are responsible for ~4.4 Gt of CO2 eq per year, accounting for 8-10 % of the global anthropogenic greenhouse gas (GHG) emissions [37, 38]. According to FAO (2011), 1.3 billion tonnes of food is either lost or wasted annually worldwide, one-third of the total food production. These levels of FLW account for 30% of the world’s agricultural land and 38% of the total energy consumption of worldwide food systems. It is possible to meet the rising demand for food and to slow down climate change by reducing these enormous volumes of FLW and improving the energy effectiveness of our food post-harvest systems. The Sustainable Development Goal 12.3 of the UN emphasises the interdependencies of reducing FLW to cut GHG emissions and mitigate against further climate change while setting a clear aim of halving food waste by 2030. Paris Agreement (2015) on climate change action also recognised the linkages between climate change, food production systems and food security. Additionally, FLW undermines the resilience and adaptation strategies for climate change that were implemented during the production stage and causes volatility in food prices, particularly in the most vulnerable regions.

Reduce FLW in such a situation by utilising climate-smart post-harvest agriculture technology, where solar-powered cold storage can be one of the change-making forces. The cooling process for cold storage requires a consistent and stable source of power, which is often supplied by the grid, diesel generators, and mechanical turbines. To replace kerosene or gas-powered cooling equipment, PV (photovoltaic) powered refrigerators were first introduced for medical uses in impoverished nations. Compared to kerosene refrigerators or diesel generators, solar cooling has the potential for cheaper running costs and a longer lifespan. Despite the fact that solar and kerosene refrigerators have nearly equal life-cycle costs, solar cooling equipment are chosen because of their reliability and environmentally favorable features. Farmers that use solar cold storage technology in agriculture are moving away from diesel-powered cooling machines, which helps to reduce environmental pollution. The Renewable Energy and Energy Efficiency Partnership [39] estimated the potential of solar cold storage for perishables in Uganda and found that despite improving agricultural production (reducing post-harvest losses), solar cold storage can save more than 100,000 tonnes (equivalent) of CO_2 a year by 2030, this avoids GHG emissions.

3.4 Social aspects

Solar energy is increasingly being used by rural areas around the world that are being impacted by climate change. Solar energy adoption is facilitated by the availability of funding options. Keeping in view the high level of GHG emissions, many Governments took initiatives to switch from fossil fuels to renewable energy. Such initiatives include energy policies and incentives for investors [40]. In 2015, renewable energy resources contributed about 19.3% of total global energy consumption [41]. Regarding employment opportunities, the renewable energy sector engaged 9.8 million people in 2016, most of them in Asia, mainly China which accounts for 62% [42]. In this regard, solar energy and biofuels created more jobs. Adoption of solar energy can also improve human health by reducing GHG emissions which cause various diseases such as cardiovascular morbidity, nonallergic Respiratory track problems, and cancer [43].

Therefore, the market potential of solar-powered cold storage units, whether centralised or decentralised, is enormous. This is because solar energy has enormous potential, as does the need to reduce post-harvest losses, the need for cooling to extend product shelf life, and the type of cooling system to be used. A market research company named "Transparency Market Research" describes the market potential of solar cold storage which is mainly based on regional and end users along with key drivers as shown in Figure 4 [44].

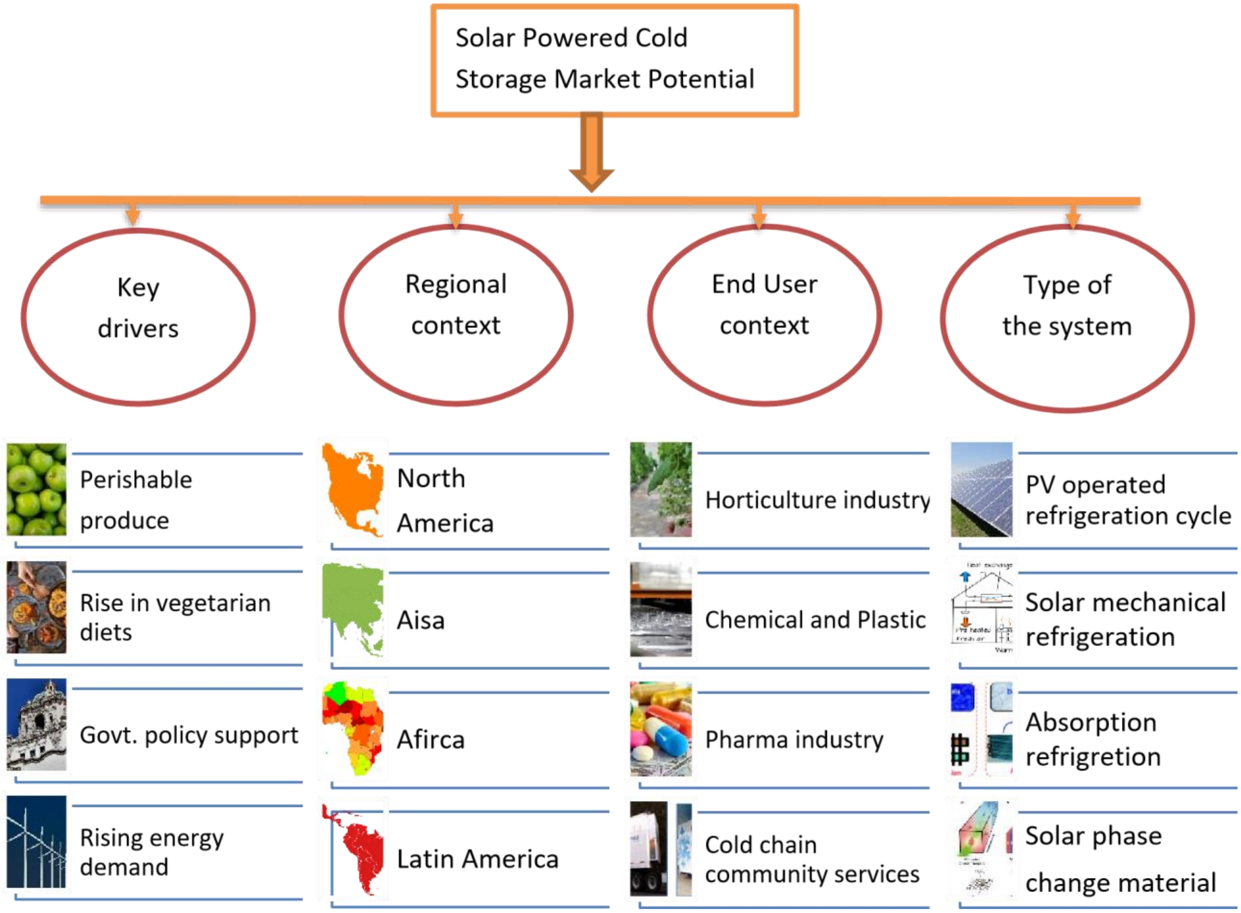


Figure 4. Parameters for the market potential of solar-powered cold storage facilities. (Reference: Adapted from Transparency Market Research [44])

4 Case studies

As was previously mentioned, applications of solar thermal and solar PV technologies are gaining popularity due to the existing scenario of post-harvest losses in fruits and vegetables and the necessity for sustainable decentralised cold storage facilities. This section contains research on solarpowered cooling systems to lower food losses at the farm gate that was done in various developing regions of the world.

4.1 Asia

The majority of the countries in Asia depend heavily on agriculture, where 40-60% population are connected with this sector for livelihood [45]. On average, 10–40% of produced fruits and vegetables are lost at various stages of harvesting, storage, and processing. For example, India, which is one of the largest producers of fruits and vegetables, possesses enormous potential to use solar energy in food handling and processing as annual solar radiation is 1200 - 2300 kW/m^2 [46]**.** For India, where 20–30% of produce is lost after harvest due to the lack of adjacent cold storage facilities, cooling-as-a-service is highly important. Regular electricity is needed to operate cold storage facilities, however grid electricity in rural locations is frequently unstable. A solution is provided by solar-powered cold storage systems, however because to the high initial cost, farmers have not embraced these systems widely. Eltawil and Samuel [47] developed a solar photovoltaic (SPV) powered cooling unit (0.18 TR, metric tonnes refrigeration) for the storage of potatoes under different operating conditions for five months. The size of the cold storage structure was 2.5m^3, and the storage temperature and relative humidity were kept at 283.13 K and 86 %, respectively. Considering a 6% loss in weight, the storage cost for a one kg product was calculated to be Rs. 9.02 /kg (1US $ = 46 Rs) using solar energy compared to the total cost occurred using electricity (Rs 7.66 /kg) and petrol-kerosene generator (14.63 Rs. /kg).

Due to their focus on storing a particular item, the majority of cold storage facilities in poor nations go largely unused for a considerable part of a year. Basu and Ganguly, [48] reported a conceptual design of cold storage unit powered by both solar thermal and solar PV energy. The cooling condition inside the storage chamber is maintained by a water-lithium-bromide-based absorption unit. Energy and exergy-based thermal analyses were performed to find out the numbers of thermal collectors and PV modules under the climatic condition of Kolkata, India. It was found that 45 parabolic trough collectors and 225 PV modules can meet the energy demand throughout the year for multi-commodity storage with a payback period of 6.22 years. This demonstrates the technically and economically viability of storing several commodities using solar energy in underdeveloped nations [49]. In another study, De and Ganguly [50] performed an environmental analysis for the same system considering four products (potato, olive, grapefruit, and multicommodity storage). In comparison to the other three storage options, it was found that employing solar energy for the storage of potatoes can reduce CO2 by 421 tonnes.

Sadi and Arabkoohsar [51] conducted a techno-economic analysis of a decentralised solar cold storage unit used for the preservation of horticultural produce in a hot humid climate. The type of solar collector was evaluated to deliver the 5 TR in yearly cooling load that is needed for the storage of the sample product, potatoes. It was found that, when 20 tons of potatoes were kept, the system integrated with an evacuated tube collector (ETC) produced the highest economic results with a payback period of eleven years. Moreover, it was also estimated that CO_2 emissions were reduced by up to 53% compared to a gas-powered chiller (absorption). A. F. Prasad [52] introduced a solar cold storage unit named *Solar Cool ColdShed*™ for small farmers and traders in Telangana and Andhra Pradesh India. It is a mobile solar-powered system that can keep goods locally at temperatures ranging from 3°C to –20°C in up to 45° C of ambient temperature. The size of the cold storage room is 10.6 m^3 and it can hold 3-5 MT food products.

Solar hybrid cold storage devices have also been found to maintain energy supply during varying solar radiation hours. Bharj and Kumar [54] designed and developed a low-power air conditioning system using PV modules for small area refrigeration. In another study, Kumar and Bharj. [53] developed a solar hybrid mobile multipurpose cold storage system. The developed system runs on grid power at night and when it's cloudy, and solar power throughout the day. Inside the cold storage cabin, phase change material (PCM) panels were installed to provide chilling even when there is no electricity. As soon as the evaporator coil cooled, PCM absorbed the energy. Depending on the ambient conditions, the PCM released the stored cooling during the power-off period to keep the cabin temperature up to -8°C for approximately 7-8 hours. Panja and Ganguly [54] proposed a solar-biomass powered hybrid refrigeration unit intending to provide a favorable cooling condition throughout the years irrespective of weather conditions. The model was developed and solved in Engineering Equation Solver for the location of New Delhi (28^{o}35’ N, 77o12’ E) and the results were validated with a reference study. India has a sizable market for the provision of cold storage facilities, but access to financing continues to be a barrier to widespread adoption of the technology. However, off-grid technologies have additional advantages for addressing the market opportunity. These advantages include a smaller carbon footprint and more reasonably priced fruits for the consumer, which will directly result in financial savings, better nutrition, and better health.

Similarly, in China, the use of PCM for maintaining cold storage conditions has also been reported. For the transportation of fruits and vegetables, Xu et al. [55] developed a polyethene cold storage plate loaded with a thermal storage substance to maintain a temperature of 5°C to 8°C. The sodium polyacrylate and multi-walled carbon nanotubes (MWCNTs) used in the thermal storage material were contained in a vacuum-insulated box. The outcomes demonstrated that the material is capable of maintaining cold conditions inside the box for 87 hours. Changjiang et al. [56] reported a cold storage structure having its walls filled with a phase change material of high latent heat density (water/ice) to maintain the cooling conditions. The unit was experimentally tested and simulated. The device underwent simulations and experimental testing. The wall's thermal resistance was altered by the installation of a PCM layer, resulting in less power being utilised.

In Pakistan, many kinds of vegetables (40 types) and fruits (21 types) are produced due to favorable agricultural climatic conditions but losses are high. The "Pakistan Agriculture and Cold Chain Development Project (PACCD)" was funded by Winrock International (https://winrock.org/), and it aimed to build a better cold storage facility for the area. The project provided the technical facility and a grant to modernise the Safina Cold Store storage facility in Quetta City for farmers to store their fruits like apples, grapes, and pomegranates before transfer to market. The expanded facility has many advantages, which has improved the market by boosting farmers' income by 40%. Munir et al. [14] developed a solar hybrid (solar-grid) cold storage unit for on-farm preservation of perishables. The size of the cold storage chamber was $21.84m^3$ which can store 2 tons of product. For cooling, 2 tons vapour compression refrigeration unit powered by a 5kWp PV system was installed. Three cooling pads were used inside the storage chamber as a thermal backup for cooling (−4˚C to 4˚C). Potatoes were stored for three months, and performance parameters were recorded. It was found that 15kWh energy was consumed out of which 70% (10.5kWh) was provided by solar energy and 30% (4.3kWh) was taken from the grid. A similar solar cold storage system was reported by Amjad et al. [57] but it was for large storage capacity (10 tons). Secondly, the installed 10kWp solar system was grid tied i.e., the system continues to produce power even when there is no storage, and this energy can be used for other farm operations. The average value of COP (coefficient of performance) for the installed refrigeration unit (3.5 tons) was calculated to be 3.95.

The People, Energy and Environment Development Association (PEEDA), which promotes sustainable development, was funded by WISIONS (https://wisions.net) in Nepal to improve the lives of the individual and the rural community. PEEDA carried out a programme to increase farmers' agricultural output by lowering post-harvest losses. Because local marketplaces are far from the producing side and Nepal's mountains make small-scale fruit and vegetable farming possible, there is a significant post-harvest loss. PEEDA introduced mobile cold storage units powered by solar energy in Dolakha District (Nepal). As a community service, the first unit allowed all the farmers to keep their food and sell it in large quantities as opposed to selling it individually in tiny amounts. It was concluded that 50% of food loss can be reduced with an employment opportunity for the maintenance and running of the units.

The Philippines' agricultural industry suffers from a high level of post-harvest losses, similar to other developing nations. Such losses can range between 20 and 40 percent for a single high-value fruit and vegetable crop. The agriculture department has introduced solar-powered cold storage facilities with an agreement with *Ecofrost* which is an Indian-based company providing on-farm solar cold storage. With a maximum PPT (Power Point Tracking) effectiveness of 99.5%, the device can deliver improved production efficiency. Low maintenance and no operating expenses were needed for the storage of 5 metric tonnes of perishables at 2^oC. The technology can deliver a battery-free backup of 30 hours, for instance in the form of phase change material. Smallholder farmers will be assisted in increasing their revenue and preserving their products as a result [58].

4.2 Africa

According to the Rockefeller Foundation, last year (2021) post-harvest losses in fruits and vegetables have been recorded to almost double in Africa, which could be related to a COVID-19 pandemic, which has affected many agricultural-based economies. Such a high increase in postharvest losses has a direct impact on the income and food security of smallholders in Africa. Relatively a higher investment has been made in tackling post-harvest losses of grains and cereals crops, however, investment is significantly lacking in the horticultural sector, particularly fruits and vegetables. The majority of small-scale farmers lose up to 60% of their post-harvest tomato crops in certain regions of Africa due to a lack of cold storage facilities [6]. Lack of access to cold storage facilities, like elsewhere in Africa, is one of the main reasons why newly harvested tomatoes rot so quickly in Tanzania. According to studies, the majority of small-scale producers use ineffective storage techniques, which can result in post-harvest tomato losses of 20% to 50% [59]. SolarPowered Cold Storage Technologies (SPCSTs) have gained widespread acceptance in recent years as a vital infrastructure to stop post-harvest losses on fresh produce, especially for small-scale farmers that live off the grid [60]. In Nigeria and, more recently, Kenya and Rwanda, it is estimated that only a small percentage of small-scale farmers have access to solar powered cold storage technologies leaving the great majority of these farmers without access to effective storage facilities to prevent food loss and waste.

In Nigeria, due to poor storage conditions at production sites, almost half of the produced fruits and vegetables are never consumed. Adekoyejo Kuye (Project Lead, Manamuz Electric LTD, https://www.manamuz.com/) said that "*The cool solution to Africa's burning problem*" is the provision of sustainable cold storage infrastructures. The agriculture sector needs to fill its energy supply shortages. The business (Manamuz Electric) designed and developed a solar-powered cold chain facility and transport system. The Coldbox Store unit has operating parameters that are tailored for the supply chain for perishable agricultural products in Africa. The facility serves as a direct interface between vendors and growers. The company aims to ensure access to affordable, sustainable, and clean energy (Sustainable Development Goals (SDG) 7) and to reduce poverty and hunger (SDG 1, 2). Similarly, Nnaemeka C. Ikegwuonu (CEO, *ColdHubs*, https://www.coldhubs.com/) developed a walk-in cold storage structure for twenty-four hours of cold storage of perishables. Insulating panels measuring 120 mm are used in the cold room to reduce cooling losses. ColdHubs is a facility where growers can store their products for a maximum of 21 days for a set fee of US$0.50 per food crate per day. It is situated in significant production and consumption locations. Until now, the company has provided services to 3517 stakeholders with its 24 units. It is also worth mentioning here, that these 24 units saved 20400 tons of food in 2019.

Hiroyuki et al. [61] conducted a project funded by the Japanese Government to increase livelihood in northeast Nigeria. This region is one of the largest producers of horticultural commodities. In this project, seven solar-powered cold storage units were installed each having a storage capacity of 3 tons of horticulture products. Each unit was integrated with a 5.6 kW PV system. The project's results revealed a large increase in product sales and user profit together with a decrease in the percentage of product loss that happened without cold storage. This demonstrates that solar energy, especially in underdeveloped countries, can be one of the practical energy sources to decrease post-harvest losses and generate cash by increasing the shelf life of harvested products.

The problem of post-harvest losses in Nigeria, which directly result in a 25% income loss for 93 million small farmers, can be greatly helped by off-grid cold-storage facilities.

In Kenya, the post-harvest losses of fruits and vegetables are estimated to be 40 to 50% [62]. According to the Kenya National Bureau of Statistics (KNBS), $1.5 billion worth of food went to waste in 2017. Dysmus Kisilu established an agri-tech company named "*Solar Freeze*" (https://www.solarfreeze.co.ke/data) which helps farmers to reduce post-harvest losses, which do not have access to better roads and electricity connections. In Kenya, 3000 women farmers were employed by the Solar Freeze facilities, which reduced losses by 50%. Another commercial cold storage unit in Kenya with facilities all throughout the country is called "FreshBox." It can hold two tonnes of fruits and vegetables. A retailer has the ability to enhance revenue by 25% and store 30–40 kg of fruit and vegetables for $0.50/crate/day as rental service.

A number of initiatives have been launched by the Food and Agriculture Organization of the United Nations (FAO) to encourage investment in developing nations' food value chains. The market potential for solar cold storage is predicted to be USD 6,150,000, according to an FAO evaluation in Rwanda. The evaluation concentrated on the nation's goal of exporting 46,000 tonnes of horticulture goods by 2024. Like many other African countries, Uganda's economy mainly depends on the agriculture sector which lacks significant investment in agro-processing industries primarily due to insufficient and non-reliable energy in rural areas. In Uganda, a solar-driven cold storage unit has been introduced by *Station Energy* under project REEP [39], the adoption of these cold storage units was a success among agricultural cooperatives and farmer groups. Similarly, another company "*Madraam Engineers limited*" developed a solar cold storage facility to store freshly harvest citrus in Amuria District, in the Eastern region of Uganda [63]. The facility's primary goal is to decrease citrus post-harvest losses during the height of the harvest by utilising the region's copious solar radiation. The constructed unit operated under two different model types. The first is for farmers who want to sell their goods directly to customers but do not have access to storage facilities. In this case, they can store the goods for Shs. 460 per kg each fortnight. This will take care of 30% of the solar cold storage facility's installed capacity. The second approach is for the business to purchase the produce from farmers and then sell it on the market after sorting, preserving, and packing it. It will take about 70% of the building's entire storage space.

Precoppe and Rees [64], developed a solar-powered environmentally controlled sweet potato curing (temperature of 28 °C and relative humidity of 85%) and storage chamber (15 °C and relative humidity at 85%) with a capacity of 5 tonnes of roots in Kenya. Instead of relying on imported goods and spare parts, the design made use of locally produced components and parts to make it simple to repair and maintain the chamber. To achieve the desired temperature and humidity, a normal air conditioner was utilised after making the necessary adjustments. Two axial fans were used for ventilation, allowing cold, moist air to continually flow through the sweet potatoes. Airflow distribution has been evaluated using computational fluid dynamics (Figure 5).

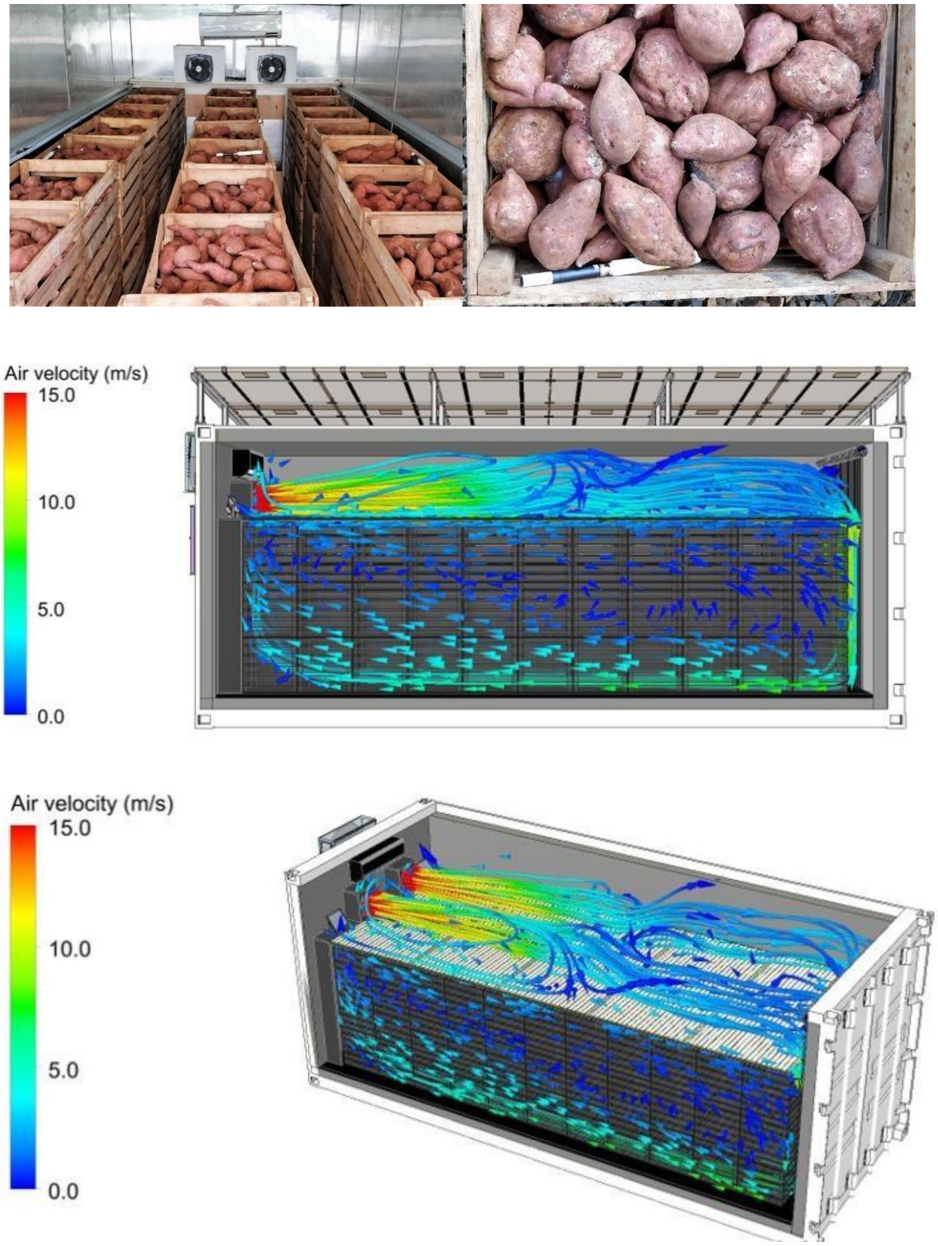


Figure 5: Internal air-flow analysis of solar cooling unit by computational fluid dynamics. ***For the CFD analysis*** *Mesh Quality: Minimum Orthogonal Quality = 2.01750e-01 Maximum Aspect Ratio = 2.47855e+01.*

Mesh Size: Number of cells = 787927, Number of faces = 4229523, Number of nodes = 2920898. (Authors own analysis, Image credit: Marcelo Precoppe).

4.3 Latin America

Food losses from post-harvest to retail in Latin America and the Caribbean have been estimated to be 20% of the world while the region accounts for only 9% of the world population. FAO report, The State of Food and Agriculture 2019 (SOFA) found that these food losses resulted in 16% of global carbon footprint, 9% land footprint and 5% water footprint. The absence of suitable cold storage facilities, which is essential to lowering both qualitative and quantitative food loss and waste losses, is one of the main causes of these losses.

Chile established the National Committee for the Prevention and Reduction of Food Loss and Waste in 2017 to streamline and coordinate initiatives to prevent food losses. A similar national program was started by Argentina in 2015 with the collaboration of more than 80 public and private sorganisations to develop a National Network to reduce food losses at various stages of its supply chain. The Inter-American Development Bank established a platform in collaboration with sorganisations like FAO, the Forum of Goods of Consumption, the Global Network of Food Banks, IBM, and other businesses to promote post-harvest interventions and innovations in the region.

Semi-Arid Renewable Energy Committee (CERSA) promoted the use of solar energy in rural district SOUSA, Brazil to generate electricity for rural development. The installed maximum capacity of 142 PV panels is 46.1 kW able to generate around 6,700 kWh per month. The system provides semi-arid regions of Brazil with market-related economic choices in addition to affordable, clean energy for a variety of uses, such as cold storage warehouses [65].

Table 2 lists the many kinds of solar-powered cold storage units that have been tried out or are now in use for the storage of agricultural produce. The cold storage units include solar thermal powered, solar PV driven, solar thermal-PV powered, solar-biogas drove, and solar thermal using phase change material.

Table 2: Types of solar-powered cold storage systems for the storage of horticultural products.

Application/ Technologies	*Product*	*Location*	*Storage Temp (^oC)*	*Cold Storage Specs.*	*Refrigeration Type*	*Energy Source*	*Ref.*

Solar Cold Storage for Food Products (Conceptual Study)	Potato	Kolkata India	10	Dimensions: 20 m* 10 m * 5 m = 1000 m3	Air-Cooled H_2O–LiBr absorption system, selected for 24-h operation	Solar Thermal and Photovoltaic (165 modules of 150 W, along with fifty numbers of FPCs of dimension: 2 m* 0.98 m)	[48]
Solar-assisted multi-commodity cold storage	Potato, olive, grapefruit	Kolkata, India	8 8 10	20 m × 10 m × 5 m	lithium bromide–water absorption system	solar thermal–photovoltaic based (46 Nos. of PTC and 275 Nos. of SPV modules of 150 Wp has)	[49]
Solar Hybrid cold storage Integrated Double-Effect Vapor Absorption System	potato, olive and grape fruit	Kolkata, India	10	20TR	double-effect VAR system	solar thermal-PVbased hybrid power system (45 numbers of PTCs of 5.8m^2 of aperture area along with 225 numbers of PV modules of 150 Wp)	[50]
SolarAssisted Cooling Chamber	Apple	Istanbul	0 to -4	1 m^3 prototype	vapor-compression refrigeration	Solar photovoltaic (SPV) solar collector; 300 Watts.	[66]
Portable solar powered cold storage room		Telangana India	3°C to –20°C	cold storage room is 10.6 m^3 and it can hold 3-5 MT	vapor compression refrigeration system	Solar PV	[52]
Solar hybrid low power refrigeration unit	multipurpose cold storage	India	-8°C	1.5 Ton	low-power Vapour compression refrigeration	Solar PV	[53]
A PV powered refrigeration facility	Milk,	Spain	0 to –4	450 l tank	VCRS COOLING BASED COLD STORAGE	Solar photovoltaic (SPV) (2.5 KW solar PV system built by 20 120W panels)	[67]

Vapour Compression Cooling System Powered by Solar PV Array	Potato	New Delhi, India		2.50 m^3 double walls store structure	Vapour Compression Cooling System	Solar PV (14 modules each) 490W)	[47]
Photovoltaicpowered cold storage unit	Fruits, vegetables and fish	India	-2	21m^3 is designed to store 10 tons of product	vapor compression refrigeration system (1 Ton)	Solar PV (134 each 30W peak)	[68]
Solar-assisted OTEC cycle for power generation and fishery cold storage refrigeration	Fruits, vegetables and fish	China	4			Ocean thermal energy conversion (OTEC) based solar-assisted combined power and refrigeration cycle	[69]
Solar–Biomass Hybrid Cold Storage-cum-Power Generation system	Potato	New Delhi, India	10		LiBr-H2O vapour absorption refrigeration system	Solar thermal and Biomass (15 kW (~5 TR) Vapor Absorption Machine coupled with a 50 KW Biomass Gasifier system)	[70]
Off-grid cold storage system integrated with an auxiliary heater	Potato	India	5	225 mm (wall), 200 mm (roof), 200 mm (floor)	Solar thermal cooling	Different types of solar collectors, cooling load is 5 TR	[77]

Energy Saving with Total Energy System for Cold Storage	fruit and vegetable	Italy	2	1,250 m^3	Vapor compression refrigerating machine and absorption system	Thermomechanical generating unit (Total energy system TES cogeneration unitIC gas-powered engine producing 300 kW)	[71]
Solar PV drove Thermoelectr ic Cooler System for Cold Storage Application	food, vaccine and milk products	Sohna, Haryana Delhi, India	10-15	Small cold storage box of 3 litre	Thermoelectr ic Cooler System	Solar PV (single crystalline solar cell PV panel, power rating of PV panel is 168Wp)	[72]
Solar powered movable cold storage	Fruits and vegetable	India	5◦C	1.83 * 1.34 * 1.98 m=4.85 m3	Movable refrigerated storage structure	Solar PV (eight solar panels of 210 Wp)	[73]
Solarpowered cold storage	Fruits and vegetable	Nigeria	7◦C	3 tons of storage	Vapor compression refrigerating unit	Solar PV 5.6 kW PV	[76]
Solar hybrid (solar-grid) cold storage unit	Fruits and vegetable	Pakistan	−4◦C to 4 ◦C	21.84m^3 2 TR	Vapor compression refrigerating unit	Solar PV-Grid 5kWp PV	[14]
Solar hybrid (solar-grid) cold storage unit	Sweet potatoes	Kenya	15◦C at 85% RH	5 tons, 6 m long, 2.4 m wide, 2.6 m high	Vaporcompression refrigeration system	Solar PV-Grid 5kWp PV	[62]
Solar hybrid mobile multipurpose cold Storage system	fish, meat, vegetables and drinks.	India	-8	0.42m*0.42m*0.54m =0.0953m^3	Vapor compression refrigeration, electric circuit for controlling conditions	Solar PV-PCM 4 panels 500 W each	[74]
Solar powered cold storage warehouse using a phase-change material	oranges	Nigeria	1	ware house: Common building bricks (150mm to 290mm	absorbent-refrigeration	solar energy thermal storage system (Phase Change Material)	[75]

				thickness)			
Phase change material based cold storage house	fruits or vegetable	China	5℃	2000mm× 1200mm× 1400mm	heat transfer resistance is 21.6kJ	solar energy thermal storage system (water/ice-PCM layer)	[18]
Solar cold storage box with nanocomposite phase change material	Yoghurt, vegetables	China	−5°C to 8°C is		The latent heat value of the PCM was 334.4 kJ/kg	solar energy thermal storage system (nanocomposite phase change material)	[55]

In figure 6 an analysis of all the publications used for this paper is presented. It shows that distribution of publications according to the energy source technology. It is clear that solar PV and hybrid systems seem to be of most interest to the researcher and practitioners. Figure 7 provides a year-wise trend in the number of publications. The trends shows that the research and development work on renewable energy based cooling systems has increased considerably in last two decades.

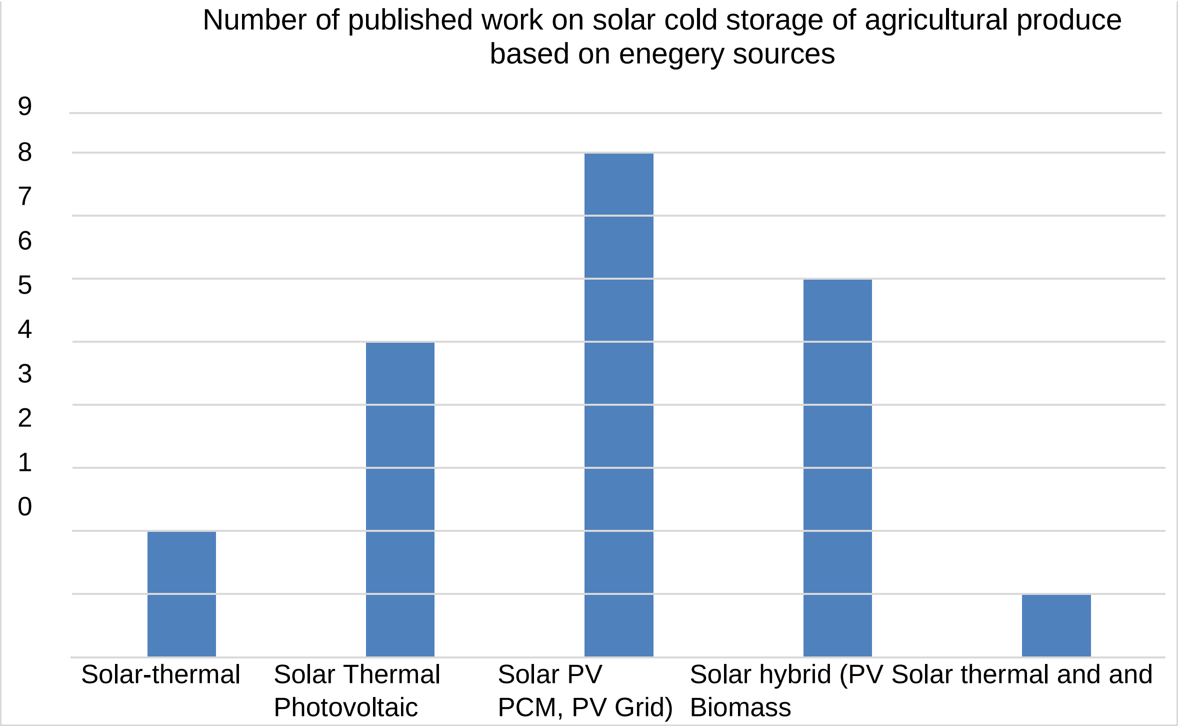


Figure 6: Number of published works reported on decentralised solar cold storages facilities based on the energy sources deployed.

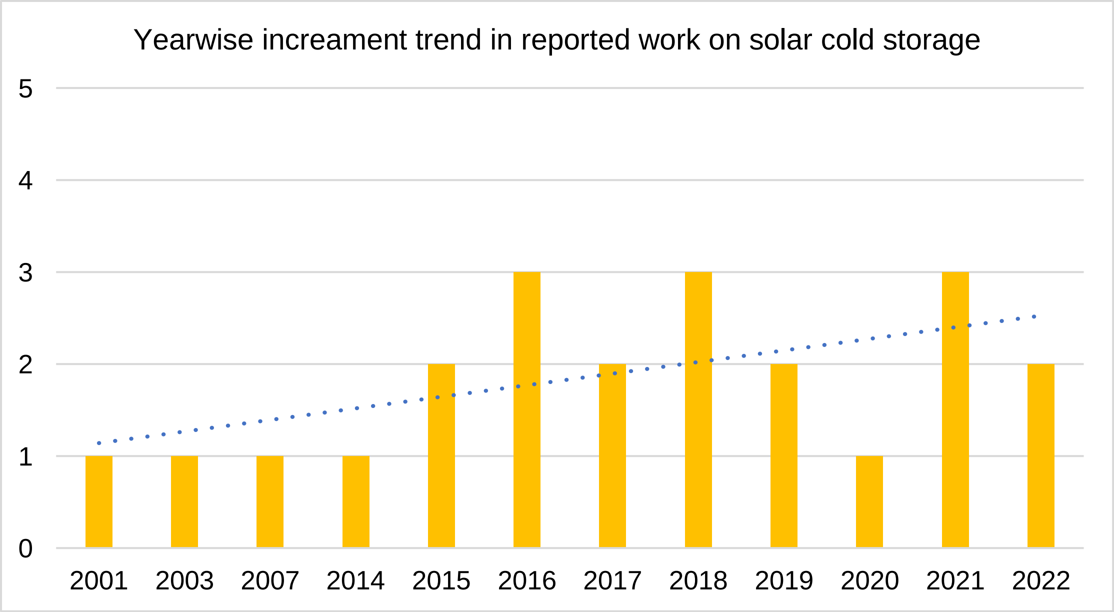


Figure 7: Year wise number of published works reported on decentralised solar cold storages facilities.

5. Operational constraints and opportunities

Technology vendors target a variety of consumer segments, and cold storage has many different applications in rural areas. The number of employees each customer group has as well as their access to equipment, land, and energy differ throughout cold chain marketplaces. Smallholder farmers often cultivate less than two hectares of land and have a limited number of productionenhancing resources. They frequently plant labor-intensive, low-value crops using basic farming techniques since they cannot get financing. This places limitations on the cold chain items' selling prices and financing alternatives to smallholder farmers [78].

According to studies, the negative opinion of stored products may result from a lack of exposure to high-quality processed foods, price considerations, the underdevelopment of the food processing sector, and cultural factors [79]. The major obstacle is getting economical, field-based cold storage facilities. Rutta EW [22] undertook a study to identify the challenges preventing the adoption and deployment of solar-powered cold storage technologies in Tanzania. Semi-structured interviews and focus groups discussion were used to explore farmers' opinions on solar technology for cooling and the barriers preventing its use. According to the findings, there is a lack of customer preference for non-refrigerated goods, high investment prices, low paying capacity among farmers, and limited awareness as barriers to the implementation of solar-powered cold storage technology.

To overcome these obstacles, policies and programs must be supported that encourage and maintain investment in cold storage technologies and increase the affordability through flexible payment options. To ensure the successful deployment and uptake of solar-powered cold storage technologies, which are currently unknown and out of reach to many in Tanzania and throughout Africa, it is important to take into account a number of issues. The assessment of these barriers offers valuable insights for decision-makers engaged in post-harvest agriculture and renewable energy programs in Africa.

The majority of smallholder farmers in sub-Saharan Africa lack access to cold storage facilities because they cannot get electricity. The problem is that, almost always, cooling depends on having access to a consistent and reasonably priced supply of either electricity or diesel fuel, both of which are frequently absent or practically nonexistent in developing countries, especially in rural areas where energy security is a serious problem [37]. The majority of developing nations in Asia and Africa continue to have poor rates of rural electrification, 65% in China & East Africa, 75% in Latin America, 87% in Middle East, 53% in South Asia and 18% in Sub-Saharan Africa (*Source:* IEA, 2010). This opens up the possibility of using solar energy for distributed cooling. In order to reduce food waste at the post-harvest stage of the food value chain, improved storage and processing technologies can be adopted more quickly with access to energy.

It is challenging to determine precisely how much food loss can be avoided by increasing access to electricity because there is a dearth of reliable and consistent data on post-harvest losses in underdeveloped nations [80]. There is huge potential of solar energy which can be transformed into rural livelihood through food handling and processing practices. According to the [81], 70 nations have good photovoltaic conditions, with long-term daily solar power potential averaging or above 4.5 kWh/kWp. Countries in the Middle East, North African region, and Sub-Saharan Africa dominate this category, accompanied by Afghanistan, Argentina, Australia, Chile, Iran, Mexico, Mongolia, Pakistan, Peru, and many countries in the Pacific and the Atlantic. The change of the global food chain is incorporating cooling technology more and more. Offering such cooling technology in underdeveloped areas like northeast Nigeria, where access to a traditional source of grid electricity has generally remained unavailable, has become more economically feasible in recent years because to the steadily falling cost of off-grid solar electricity [76]. Financing options for renewable energy projects have greatly expanded during the last ten years. The portfolio of investments in renewable energy and other environmentally friendly technology has greatly increased at the World Bank and other multilateral finance organisations.

In the global food chain, the Asia Pacific area supplies 19% of all food and 31% of all agricultural exports and imports. The demand for agricultural and food products and resources is increasing across Asia as a result of the region's largest and fastest-growing population. In this market, a solar-powered cold storage device might revolutionise the industry [82]. Similarly, high production and import of agricultural products in the Middle East & Africa region are made possible by water-efficient irrigation systems and rising food demand, which can be attributed to rising demand for the global solar powered cold storage market.

A key social risk linked with solar energy technologies is sociocultural unfamiliarity with technologies and hesitancy to try new solar technology possibilities [83]. The societal consequences like reduce food waste, increase local farmer income, reduce malnutrition, and jobs for women can be achieved using sustainable cooling technology, but end users must be motivated to do so (*ColdHubs* https://www.coldhubs.com/). Various operational issues in terms of economic, social, technical and local environment are involved in the successful deployment of solar cold storage facilities at farms along with potential opportunities of success as summarised in Table 3.

Table 3: Operation of solar-powered cold storage systems for horticulture products: limitations and prospects.

Operational constraints	Economic	High initial cost	A solar-powered cold storage system has a higher overall cost than a conventional cold storage system by 30% to 50%. The lack of domestic manufacturing facilities for solar hardware devices is the major cause of this high price.	[22], [84], [85], [88]
		End user affordability	When such facilities are introduced to local community, farmers face a significant barrier in terms of affordability to adopt and employ solar-powered cold storage technology.	
		Energy enterpriser	There is a lack of access to funding and equity for renewable energy businesses who want to support these farmers' growth.	

		Uncompetitive market	The adoption of decentralised offgrid cold storages has also been hampered by an uncompetitive market. Because the majority of these systems are developed, operated, and maintained by private companies, it is critical for the government to collaborate with the private sector to remove market obstacles.	[36]
	Technical	Energy intensive process	Compared to other clean energy technologies like solar house lighting, agro-processing, and water pumping, cold storage equipment runs almost continuously and needs more energy availability. Chillers for smallholder farmers are 50 to 250 percent more expensive than the solar irrigation pumps.	[85], [86] [89]
		Intermittent nature of the solar energy	The intermittent nature of solar energy is a major concern. Because of its irregular behavior, solar energy is not regarded a reliable	[85]

			source of energy and so is not a good choice for continuous power delivery.	
		Battery backup	Solar cooling in the form of a standalone system is expensive due to the large size of battery backup. These batteries need to be replaced every 3-5 years, contribute for 30 to 40% of the total cost.	[21], [87], [88]
		Distribution	Since sustainable energy technologies are still in their infancy, farmers have only a few options for distributors that can provide installation, parts, and servicing. There is lack skilled manpower.	[83], [91]
	Social	Fresh food preference	Experts and farmers believe that the customer desire for fresh produce (non-refrigerated fruits & vegetables) could pose a significant barrier to the widespread adoption of cold storage.	[22], [92]
		Skeptical behavior	Before it leaves the farm gate, a sizable portion of the harvest produced by smallholder farmers is lost to spoilage. However, they frequently have doubts about the necessity of cold storage and the viability of using clean energy to run farm equipment.	[86]
		Lack of awareness	Agriculturalists are unaware of the diversity of new technology that could be useful to them especially renewable energy-based technologies.	[79]
		Scattered community	Energy businesses have challenges due to remote and scattered rural communities which is often very poor.	

	Environmental	Data availability	Geographical location has a significant impact on solar energy. So, without thorough feasibility assessments, solar systems cannot be installed. It is also challenging in developing regions to obtain accurate environmental data, which is essential for utilising solar energy.	[85]
Opportunities for success	Demand of leavy foods	Transition toward vegetarianism across the globe has increased the demand of fruits and vegetables. In order to meet the demand, the existing losses in the field can be reduced through decentralised storage facilities.		
	Energy demand	Exploration of new energy sources has increased as a result of an increase in energy demand around the world. This will probably propel the market for solarpowered cold storage. Cooling is the most efficient approach to reduce the rate of spoilage, however implementing cold storage in rural areas of developing nations has a more serious problem because of the absence of consistence electricity.		[36]
	Need of food value chain	Lack of adequate cold storage is a bottleneck in many developing nations that results in food losses through biological deterioration and jeopardises farmer income. Perishable goods including fruits, vegetables, and dairy have very high food loss rates due to improper cold storage. For sustained nutrition, there must be a functional food value chain. This aspect triggers the need of decentralised handling of food.		[77]
	Short payback period	Farmers do not have access to finance for upfront payments to purchase the system, off-grid solar makes the system capital demanding. However, the short payback period (less than two years) creates a compelling business case, and if farmers have access to the financing facility, the cold chain might be more widely used in rural areas.		[84]
	Agricultural development	One of the most significant factors influencing the growth of the solar powered cold storage industry is agricultural development. A third of agricultural output is lost due to deterioration. Farmers may reduce produce waste and enhance storage quality with solar powered cold storage, which has ultimately led to a rise in demand for this type of facility.		[82]

	Business model	The affordability issue can be solved with a smart business plan that satisfies consumer demands and is within their price range. Implementing suitable payment plans could persuade many low-income people to accept solar items that they consider to be very pricey. Promoting regulations like reducing import taxes on solar technology components would be essential for expanding the market and luring additional solar service providers to start offering and implementing solar technologies. Instead of selling refrigerated equipment, innovators can develop business strategies that offer chilling as a service. By eliminating the requirement for consumer financing, chilling services would allow customers to	[36], [83]

		pay for the chilling equipment only when it is really used.	
	Awareness of technology	It is vital to inform potential users about the financial advantages of utilising solar-powered cold storage technology and to promote and raise knowledge of these advantages. Prior to deployment, it would be essential to raise public awareness and educate consumers about solar powered cold storage solutions in order to promote demand and uptake for such technologies among other market segments besides farmers.	[85]

It is worth noting that, in order to make the most of these opportunities, it is important for the systems to be well-designed, well-maintained, and operated by trained professionals. Data regarding the most prevalent constraints have been examined based on the studies stated above. For this, the records were gathered, the duplicates eliminated, and the papers or reported work were vetted to get rid of anything not specifically connected to decentralized solar cold storage systems. Out of nine selected studies, each constraint received two marks if it was mentioned as the study's primary constraint and one mark if it was mentioned as a partially dominant constraint. Figure 8 shows that economic constrain has been reported as dominant one followed by technical constraint.

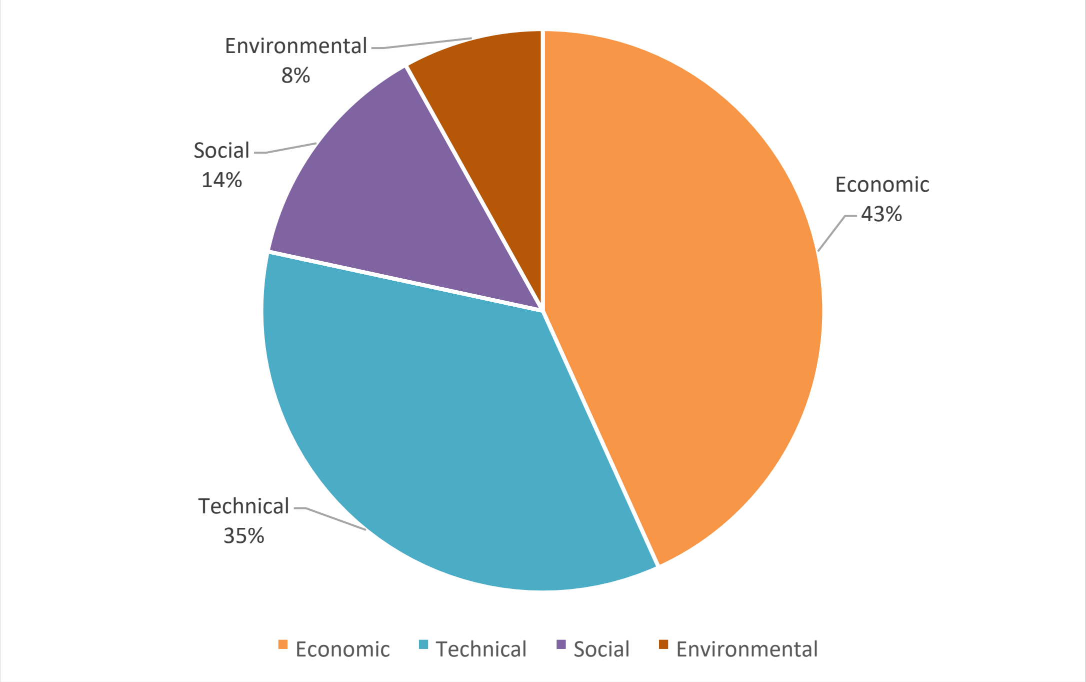


Figure 8: Percentage of prevailing operational constraints for the successful deployment of decentralized colsd storage facilities in developing regions

6. Conclusion

The study summarised that in developing regions, the most important factor causing postharvest losses in fruits and vegetables is their bulk storage at production sites and then transportation to long-distance markets in a non-refrigerant environment. There is a dire need to handle the horticultural produce safely at production sites. Various public and private sectors are working to use solar energy for cold storages. In spite of dire need of this sustainable technology, the viability of cold storage infrastructures becomes difficult due to the fragmented farming practices in developing countries leading to poverty.

Solar powered cooling facilitates can play a vital role to address the challenge of food security through decentralised storage of horticultural commodities. It not only helps in the reduction of food loss and waste but also supports green economic growth by reducing GHG emissions. In this aspect, Asia, particularly India, has done more work than Africa and other developing regions. The lack of cold storage facilities in rural areas is related to operational challenges caused by inconsistent grid supply and the difficulty in getting financing for the construction of solar-powered cold storage systems. The key barrier faced in the uptake of such systems is the high upfront cost. These obstacles need to be overcome like the provision of affordable finance to farmers and incentivising the stakeholders. Possible solutions include the development of adequate technology to meet the needs of cold storage, creative finance to make cold storage systems affordable, and a supportive business/enterprise/market environment to enable the deployment of the solutions successfully.

Moreover, following recommendation have been conceived from the study,

- Governments must pass specific legislation to promote the use of renewable energy for cooling along the entire agri-food supply chain to improve consumers' and financial institutions' confidence.
- In order to make cooling solutions available to small-scale farms, stakeholders (public, corporate, and financial institutions) must simultaneously encourage financial innovation like blended finance.
- Moreover, effective cooperation and communication between key players and agricultural organisations like extension departments need to accelerate through effective training program on significance of off-grid solar technologies.

- It has been determined that the majority of regions have a sizable cold storage capacity, but it is primarily devoted for the long-term preservation of particular crops, like potatoes. Small-capacity, decentralised cold storages in or near villages are needed instead. These short-term transitional storages would assist small and marginal farmers by allowing them to store their horticulture products during times of surplus or when the produce cannot be transported to demand centers due to any limitations or disruptions.
- Analysing an intervention's technical and economic applicability in a particular country or location, as well as the size at which it would work, is a crucial step before adopting it. This is essential since the cost of a storage, value-added, and processing technology or infrastructure varies greatly depending on the level of local skill and the level of development of the nation.

Declarations

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Conflicts of interest/Competing interests

All the authors declare no conflicts of interest or any other competing interests.

Data availability

Not Applicable

Code availability

Not Applicable

Authors' contributions

Conceptualisation: [Wasim Amjad, Fatima Akram, Furqan Asghar]. Methodology: [Anjum Munir Faisal Mahmood], Formal analysis and investigation: [Wasim Amjad and Fatima Akram], Writing - original draft preparation: [Wasim Amjad and Fatima Akram]; Writing - review and editing:

[Aditya Parmar and Marcelo Precoppe]; Funding acquisition: [Anjum Munir and Faisal Mahmood]; Supervision: [Faisal Mahmood and Anjum Munir]. All authors read and approved the final manuscript. **References**

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